

## THERMOACOUSTIC STREAMING AND ULTRASONIC PROCESSING OF LOW MELTING MELTS

E.H. Trinh

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, CA

### ABSTRACT

Ultrasonic levitation allows the processing of low melting materials both in 1 G as well as in **microgravity**. The free suspension of the melts also facilitates **undercooling**, permitting the measurement of the physical properties of the **metastable** liquids. A convenient method to melt a levitated sample involves its spot heating through a focused radiant source, the heat input to the sample is controlled by the material **emittance** as well as the external convective flows. Because of high intensity sound fields required for levitation, **thermoacoustic** streaming will significantly increase the heat transfer from the **sample** to the environment, and it **will** therefore decrease the heating efficiency. Experimental measurement involving flow visualization and power input monitoring have allowed the quantitative assessment of this enhancement in heat transfer at ultrasonic frequencies and for millimeter-size samples. A decrease of temperature by up to 150 C for a sample initially at 550 C without the sound has been measured. Other results involving normal 1 G and low gravity flow visualization and material processing are presented.

### INTRODUCTION

A low gravity environment is ideally **suited** for experimental studies involving the melting and solidification of materials in the absence of a container. The drastic reduction in the effects of the Earth gravitational acceleration allows the use of much lower levels in the electromagnetic <sup>1,2</sup>, electrostatic <sup>3</sup>, or acoustic <sup>4</sup> fields used to remotely position the **sample** of interest. Depending upon the material properties, the composition of the processing medium, and the levitation technique, the reduction of gravity could allow the study of **phenomena not ordinarily** observed, or **it** could lead to

more accurate experimental measurements. For example, the decrease in the magnitude of the electromagnetic field required for positioning a molten metal droplet in low gravity could result in the enhanced supercooling of the liquid sample. The reduction of the acoustic intensity used for sample levitation in a gaseous host medium also means a reduced level of acoustically induced convective flow around the levitated sample. The effects of acoustic **streaming associated** with ultrasonic levitation is the subject of this experimental investigation,

The specific results to be reported below have been obtained from a flow visualization study of streaming flow fields in a single-axis ultrasonic **levitator** operating at 25 kHz and in 1 G. A quantitative assessment of the enhanced convective **heat** transfer from a locally heated sample has been obtained for moderately high sample temperature, and the results are summarized. Finally, some results of the levitation processing of low-melting materials in 1 G using ultrasonic techniques are described.

### 1. THE EXPERIMENTAL TECHNIQUE

A standard single-axis ultrasonic levitator (Trinh, 1985) is used to levitate the liquid and solid samples to be processed in a gaseous environment and at the focus of either a **Nd-Yag** laser or a Xenon arc lamp. Figure 1 provides a schematic representation of the apparatus. An ultrasonic standing wave with an integer number of **half-wavelengths** (typically 2 or 3) is established between the driver and reflector, and a sample can be levitated at any one of the pressure nodes (acoustic velocity **antinodes**). A radial dependence of the acoustic pressure distribution, due to natural beam divergence as **well** as due to the curvature of the **reflector**, generates a lateral restoring force used to center the sample along the symmetry axis of the levitator. In addition to the second-order radiation pressure which is at the origin of the levitation force, a second

order steady-state convective flow, or acoustic streaming field, is also generated. These flows are the ultrasonic equivalent of the streaming flow fields investigated by Gopinath and Mills<sup>5</sup> (1993) in the same context of the application of acoustic levitation. The visualization of these flows is carried out through light scattering by smoke particles under a laser sheet illumination. The resulting streamlines are imaged by a video camera and recorded on tape,

The temperature of the heated samples is determined through embedded thermocouples when they are mechanically suspended, and by the use of an infrared imaging camera when they are levitated,

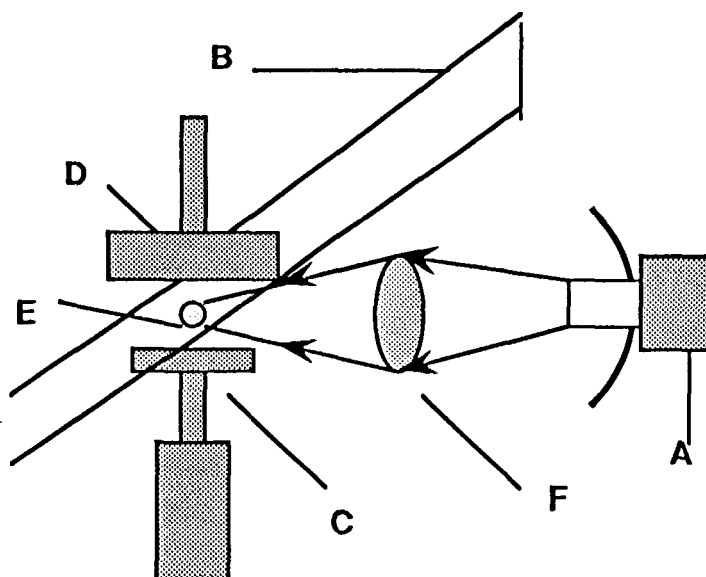


FIGURE 1

**SCHEMATIC DESCRIPTION OF EXPERIMENTAL APPARATUS. THE SAMPLE (E) IS LEVITATED IN THE AXISYMMETRIC STANDING WAVE BETWEEN THE ULTRASONIC DRIVER (C) AND THE REFLECTOR (D). THE LIGHT SHEET (B) IS USED TO VISUALIZE THE FLOW FIELD THROUGH SCATTERING FROM SMOKE PARTICLES. A XENON ARC LAMP (A) BEAM IS FOCUSED ON THE SAMPLE THROUGH A LENS (F).**

## II. FLOW VISUALIZATION OF THERMOACOUSTIC STREAMING

Incense smoke was used as a tracer for these flow visualization studies. Previous investigations under isothermal conditions have revealed that the axial symmetry of the levitator was extended to the acoustic streaming flow field. This symmetry would not necessarily be preserved, however, in the case of a locally

heated levitated or mechanically held sample because the spot heating is generally not along the axis of symmetry. With this caveat in mind, we have carried out flow visualization using sheet lighting parallel to the levitator axis of symmetry which is vertically oriented parallel to the gravity axis. The heated sample was simulated by a cylindrical mechanically held thermistor (1.9 mm diameter and 6.35 mm long). The temperature of the thermistor was varied by changing its drive voltage; its resistance was monitored by measuring the current input. All experiments were carried out at an ambient room temperature of about 23 C.

The ultrasonic frequency was 25 kHz and the maximum Sound Pressure Level or SPL was 155 dB. The SPL is defined as a logarithmic relative pressure measurement with a fixed reference  $p_{ref} = 0.0002 \mu\text{Bar}$  expressed in dB.

Figure 2 is a photograph of a video frame showing the flow pattern around the unheated cylindrical thermistor with ultrasound at 145 dB. The sound driver and the reflector can be seen at the bottom and top of the picture together with the primary and secondary eddies. An enclosure has been placed around the levitation region in order to slow smoke dissipation. This enclosure does not significantly contribute to the primary standing wave in the region of interest around the sample. The primary set of eddies would be present in the chamber even without the thermistor, while the secondary eddies are attached to the thermistor and are caused by its presence. The primary eddy flow direction is counter-clockwise on the right side and clockwise on the left side of the picture; the direction of flow in the secondary eddies is directly opposite. Theory predicts a symmetrical set of vortices above and below the cylinder for streaming around a cylindrically shaped body. In practice, the superposition of the primary streaming flows caused by the enclosure reinforces the upper set of eddies, but opposes the lower vortices.

Figure 3 shows a still video frame for a thermistor heated to 150 C in an ultrasonic standing wave with the SPL at 140 dB. In addition to the secondary vortices attached to the upper part of the thermistor, a lower set of vortices reappear on the lower side of the thermistor. This reappearance of the lower vortices is probably due to natural convective flows coupled to the temperature gradient caused by the hot sample immersed in a cooler gas environment.

Figure 4 shows the streaming flow field immediately around the thermistor for a temperature of 450 C and the SPL at 145 dB. The upper eddies are no longer prominent, but the lower eddies are sharper and detached from the sample. These lower eddies are also split into two sets of counter-rotating vortices. The outer component of this pair periodically stretches outward, sheds, and reforms closer to the inner component. The frequency of vortex

shedding is controlled by the tuning of the ultrasonic standing wave. For a given sample temperature, a steady flow pattern can be established and maintained if careful tuning of the ultrasound is implemented. The flow pattern away from the sample is also significantly **modified** by the addition of heat transfer. The influence of natural convection manifests itself through the shift in the location of the attached secondary **vortices**: free convection induces a flow opposite to the original primary streaming flow of the isothermal chamber and reinforces the lower set of secondary vortices while washing out the upper pair. In a **low** gravity environment the morphology of the flow would be strictly dictated by the primary streaming established by the ultrasonic wave and the walls of the enclosure.



FIGURE 2  
FLOW PATTERN AROUND THE UNHEATED CYLINDRICAL THERMISTOR WITH AN ULTRASONIC WAVE AT 145 dB.



FIGURE 3  
FLOW PATTERN AROUND THE THERMISTOR HEATED TO 150 C WITH SOUND AT 145 dB.

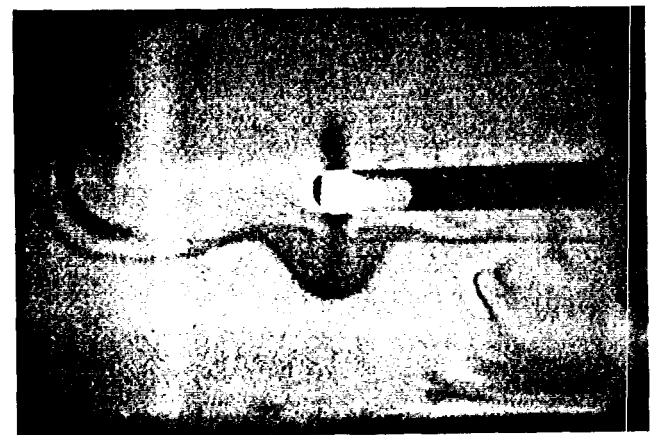
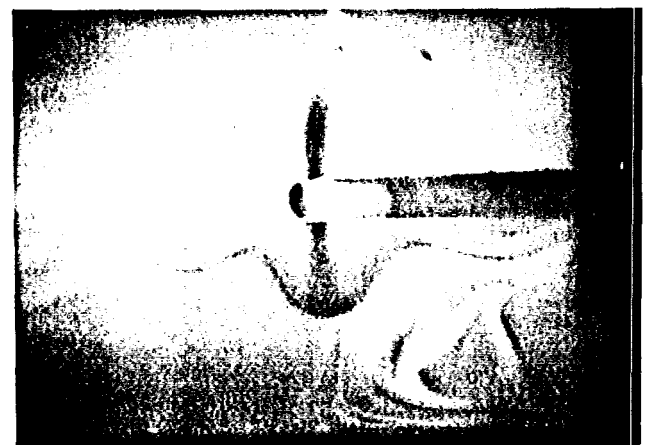
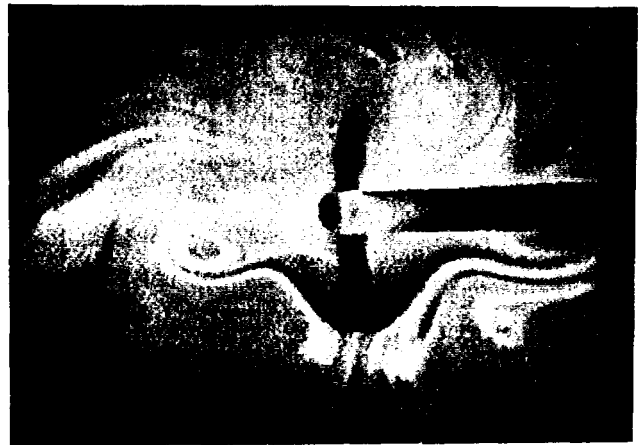


FIGURE 4  
FLOW PATTERN WITH THERMISTOR AT 450 C AND SOUND AT 145 dB

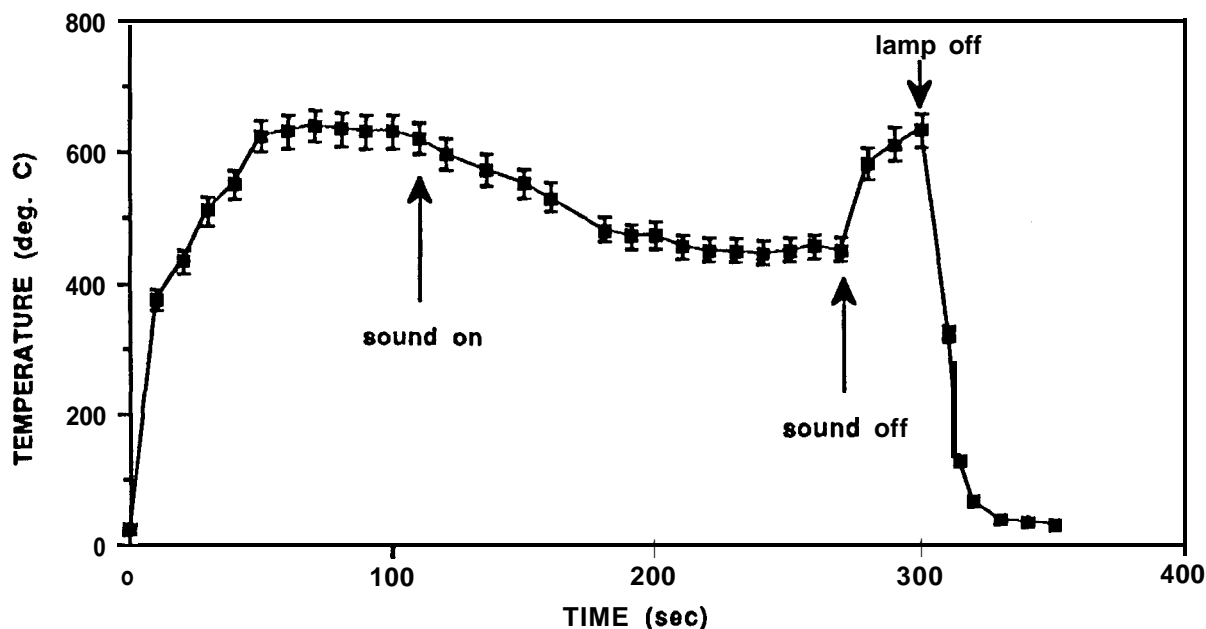


FIGURE 5  
TEMPERATURE OF A SPOT-HEATED CERAMIC SAMPLE WITH AND WITHOUT THE ULTRASOUND AT 160dB

### III. THE EFFECT OF STREAMING ON FORCED CONVECTIVE HEAT TRANSFER

Figure 5 displays the results of the measurement of a spot-heated ceramic sample mechanically held at the pressure node (velocity antinode) of an ultrasonic standing wave at 160 dB. The sample was heated by focusing the light from a Xenon arc lamp on one side of the sample. The temperature was obtained from a thermocouple embedded in the spherical sample of 3 mm diameter. A dramatic drop in the sample temperature from 640 to 440 C (45% decrease) illustrates the effectiveness of forced cooling by ultrasonic streaming, and it explains why forced convection must be included in the heat transfer calculations aiming to predict the incident power required for heating a sample with a given size and emittance to a specific temperature. Low gravity will again modify the initial conditions by lowering the maximum Sound Pressure Levels required for positioning of a sample, and this enhancement of the heat transfer will be attenuated in microgravity.

In order to simulate the microgravity conditions, additional measurements were carried out using the mechanically held thermistor and relatively low SPL (145 dB). At 25 kHz and 145 dB in air at 25 C the Stokes

boundary layer thickness  $\delta$  ( $\delta = (2\nu/\omega)^{0.5}$ , where  $\nu$  is the kinematic viscosity of the fluid, and  $\omega$  is the angular frequency of the acoustic wave) is approximately equal to 14  $\mu\text{m}$  and the acoustic displacement amplitude is about 35  $\mu\text{m}$ . Defining a streaming Reynolds number in the same manner as Gopinath and Mills<sup>5</sup> (1993) and Leung et al.<sup>6</sup> (1989):  $R_s = a/\delta$ , we find that the value for  $R_s$  is approximately equal to 4 for our measurements at 145 dB in air for a thermistor heated to 420 C.

Assuming that the thermistor is isothermal, an average Nusselt number can be calculated.  $Nu = hd/K$ , where  $h$  is the average heat transfer coefficient,  $d$  is the thermistor diameter, and  $K$  is the thermal conductivity of air. The average heat transfer coefficient is based on a cylindrical geometry, and can be expressed as:

$h = Q / A_c (\Delta T)$ , where  $Q$  is the power input,  $A_c$  is the surface area of the cylinder, and  $\Delta T$  is the temperature difference between the thermistor and the ambient air. The results are listed in table I for four different temperature differences between 57 and 397 C. Although the analysis of Gopinath and Mills is based on a spherical geometry, for small temperature differences, and for much larger values of  $R_s$ , the ratio  $Nu / (R_s)^{0.5}$  was calculated for comparison. As shown in table I, the calculated ratios differ from the theoretically derived value of 1.10 for air 5.

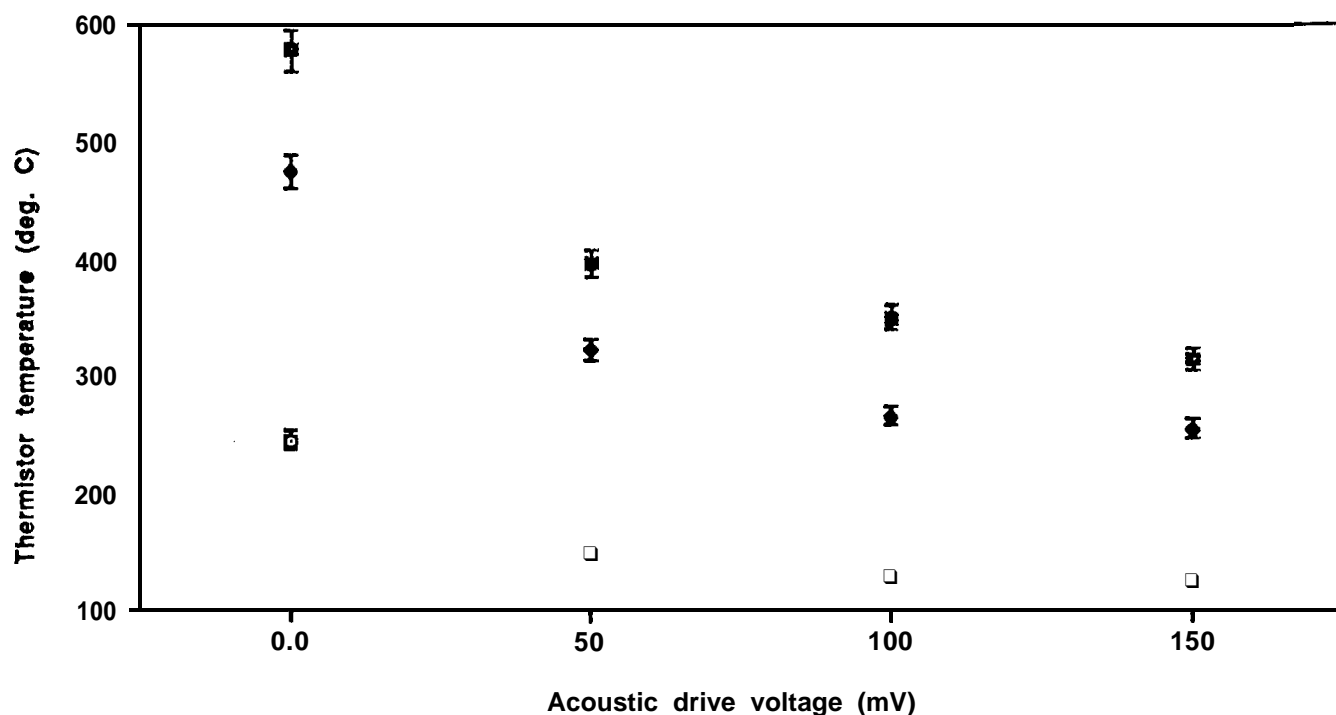


FIGURE 6

THERMISTOR TEMPERATURE AS A FUNCTION OF ACOUSTIC DRIVE FOR DIFFERENT INITIAL TEMPERATURES

#### IV. DISCUSSION

Previous experimental studies of thermoacoustic streaming have also included flow visualization and heat transfer coefficient measurement <sup>7,8</sup>. Most of these results were obtained for a horizontally directed *traveling* sound wave normal to the axis of the cylinder and for a ratio of the acoustic half-wavelength to the cylinder diameter which is at least equal to 6 ( $\lambda/2d$  is equal to 3 in this present work). The ratio of the acoustic particle displacement to the diameter of the cylinder  $a/d$  was equal to 0.016 in the previous work while it ranges from 0.019 to 0.028 in the current investigation. In addition the previous flow visualization results were obtained with flowing smoke streams while the present ones have been based on initially stationary smoke particles. The previous studies could not therefore reveal the superposition of isothermal streaming with the thermoacoustic component. These differences explain why the current measurement of the average heat transfer coefficient for forced convective cooling yield results which are a factor of 5 larger than the values obtained in the earlier studies.

$\Delta T(^{\circ}\text{C})$	$h(\text{W}/\text{m}^2\text{K})$	$Nu=hd/\kappa$	$Nu/(R_s)^{0.5}$
57	63	4.13	1.99
132	125.6	7.02	3.46
307	155.6	6.70	3.74
397	165.4	6.41	3.75

TABLE I

RESULTS OF THE CALCULATION OF THE AVERAGE HEAT TRANSFER COEFFICIENT AND THE AVERAGE NUSSELT NUMBER FOR FOUR DIFFERENT TEMPERATURES.

The **current flow visualization results suggest that natural convection plays a significant** role in the determination of the morphology of the flow field: the resulting flow configuration is a superposition of the isothermal streaming field, natural **convective** flow, and the **streaming flow** associated with the sample itself. The principal controlling parameters are the temperature difference  $\Delta T$  and the acoustic **particle** displacement amplitude relative to the sample diameter  $a/d$ . For moderate temperature differences ( $\Delta T \approx 500^\circ\text{C}$ ), two distinct flow field regimes appear to dominate near the sample: asymmetric **pattern** of four eddies both above and below the sample at lower sound intensity ( $\text{SPL} < 145\text{ dB}$ ) and an asymmetric distribution where two sets of counter-rotating **eddies** are found at the lower half of the sample. Vortex shedding can happen, and it is probably related to the stability of the standing ultrasonic wave under thermal fluctuations. Careful tuning of the acoustic wave always appears to stabilize any large scale oscillation of the flow field. One must keep in mind that the quasi-isothermal streaming flow field characteristic of the chamber provides a background which must be taken into account in the detailed analysis of the overall fluid flow distribution. At very high sound levels ( $\text{SPL} > 150\text{ dB}$ ) the smoke particle **visualization technique** is no longer effective because of the high velocities attained, and no **clear** structure can be resolved. It seems, however, that the lower vortex **pattern** attached to the sample still remains, even in the **midst** of what would appear to be **turbulent** flow.

## V. SAMPLE Processing EXPERIMENTS

Ultrasonic levitation melting, **undercooling**, and solidification in a gaseous environment of low melting metals, and organic or inorganic materials have been carried out in ground-based laboratories in isothermally heated chambers<sup>9</sup>. Spot heating of **levitated** samples is more **difficult**, however, because of the local thermal disturbance affecting an essentially rather well tuned system. The non-trivial task of maintaining levitation under the **influence** of **thermo-acoustic** streaming has been investigated in 1 G, and it can be accomplished for a sample-environment temperature difference of about  $500^\circ\text{C}$  for **low** density materials. This implies that the microgravity implementation of such a capability has been verified. The extension to higher temperature processing could **be** accomplished through the combination of a high temperature isothermal facility coupled to a spot heating capability.

The spot heating of materials for **containerless** processing is advantageous in terms of high heating and

**cooling** rates, but it presents the disadvantage of requiring the implementation of reliable remote temperature measurement capabilities. In addition to standard single and multi-color pyrometers, we have chosen to implement **infra-red** imaging cameras for high temperature Earth-based developmental studies as well as for experiments in material processing.

Figure 7 reproduces video displays of an **infra-red** imaging camera recorded during the levitation melting of a spherical **polymer** sample in 1 G. The sample starts to soften and increases in volume due to boiling of volatile components. It ultimately distorts and solidifies into a non spherical sample.

Because of the thermal input from the spot heating, the ultrasonic standing wave undergoes oscillations which cause sample translational vibrations. These positional instabilities (also accompanied by rotational motion) in turn initiates thermal fluctuations because the sample has a time-dependent motion into and out of the heating beam or **focal** region. Earth-based processing is more sensitive to this instability process because of the high sound pressure **levels** required for levitation. The practical solution to this problem involves real-time, fast response, ultrasound retuning as **well** as slow increases in the **heat input**. A closed-loop feedback **system** coupling the sound tuning and intensity to the sample motion and heat input is required for Earth-based controlled processing. The sample behavior in microgravity should remain qualitatively similar **except** for slower positional fluctuations due to the smaller magnitude restoring force. The same active control capabilities for the levitator and heat input, however, will still be required.

Figure 8 are photographs of the **IR imager** output for the Earth-based levitation heating of a low density shuttle **tile** sample (3 mm in diameter). The series of photographs shows the typical fluctuations in position of the sample. The maximum temperature recorded is approximately  $520$  to  $550^\circ\text{C}$ . A substantial thermal gradient exists on the surface of **the** sample as it is heated from one **direction** by a 2 mm diameter gaussian beam from a **Nd-YAG CW** laser.

Figure 9 shows the various stages of melting and solidification of an **O-Terphenyl** sample in low gravity during the parabolic flight of the NASA KC-135 airplane. About 15 seconds are **available** at an acceleration level of about  $0.05\text{ G}$  for positioning, melting, and solidifying the sample. The resulting **oblate** shape is caused by the higher intensity sound required for levitation under  $1.8\text{ G}$  during the high G part of the parabolic flight.

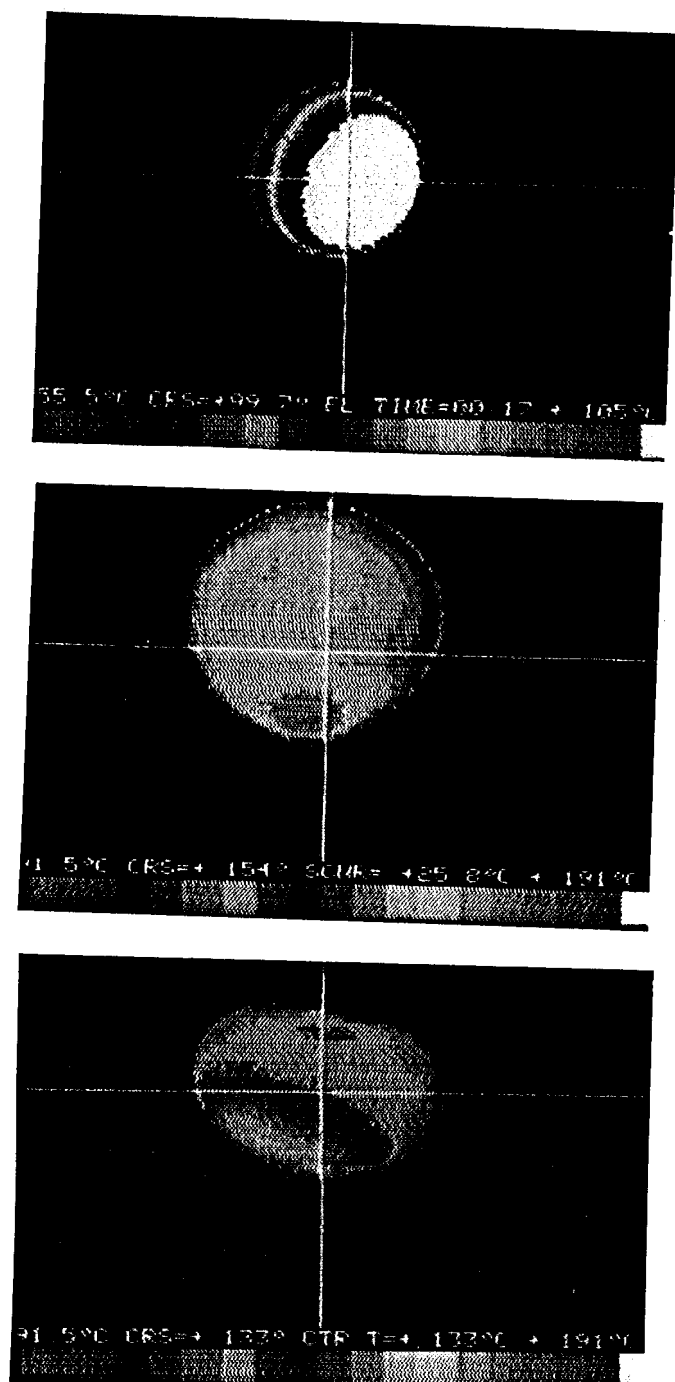


FIGURE 7

LEVITATION PROCESSING OF A SPHERICAL  
POLYMERIC SAMPLE IN AN ULTRASONIC FACILITY  
WITH FOCUSED XENON ARC LAMP HEATING

## VI. SUMMARY

These preliminary experiments have provided strong evidence for the significant role played by **thermo-acoustic** streaming in the levitation processing of materials. Flow visualization has **shown that the resulting convective field is** a combination of forced isothermal streaming characteristic of the chamber, near sample boundary streaming, and finally natural buoyancy flows. The reduction of the gravitational component thus significantly alters the flow morphology by virtually eliminating the natural buoyancy component and by reducing the maximum acoustic field intensity required for sample positioning.

Results of the measurements carried out in this work also suggest that the enhancement of heat transfer quickly increases for sound pressure levels up to 150 dB, **but** levels out at the very **high SPL**. Since the lower end of the sound intensity scale is likely to be implemented in low gravity, the effect of **thermo-acoustic** streaming should remain an important factor in **microgravity** processing of materials in gases. **Thermo-acoustic** streaming **affects not** only the efficiency of spot heating of freely suspended samples, but it also significantly degrades their positional and rotational stability within the ultrasonic field. An appropriately designed feedback **system** tying the sound tuning and intensity and heat input controls to sample positional information will be required for both ground-based and **microgravity** processing.

Earth-based processing of low-melting polymeric and metallic materials has provided **early evidence** of the feasibility of spot heating for moderate sample-environment temperature difference. An **experimental** I y determined upper limit of about 500 C for the sample-environment temperature difference has been obtained for ground-based processing of low temperature samples. The environment temperature can of course **by as high as** required as **long as isothermal conditions are maintained and the positioning (levitation) system remains effective.**

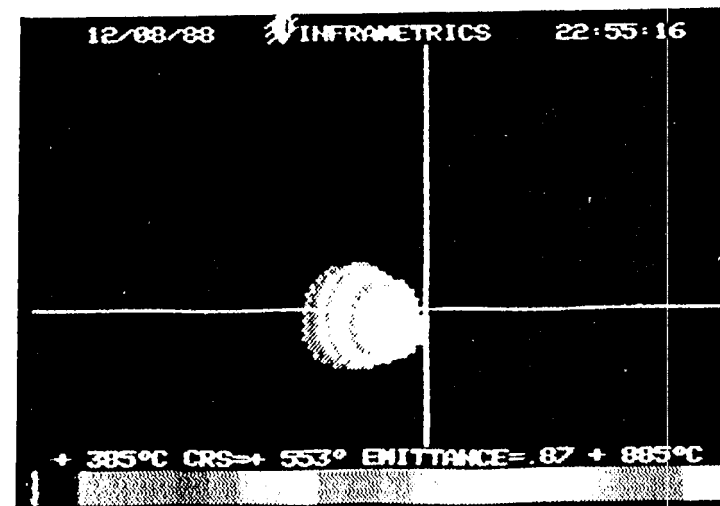
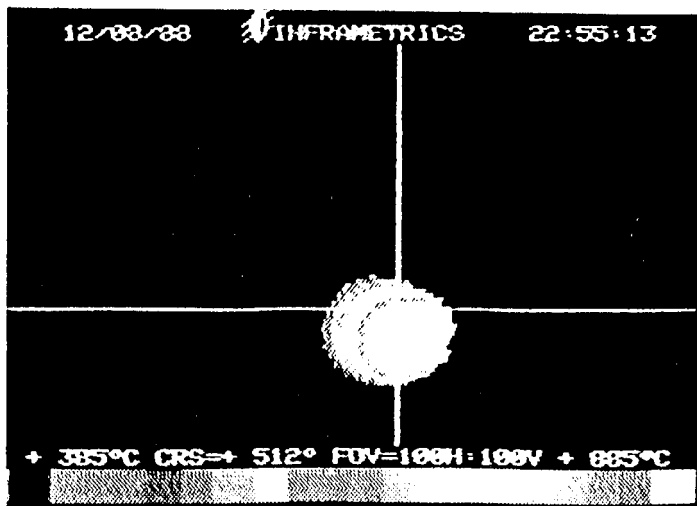
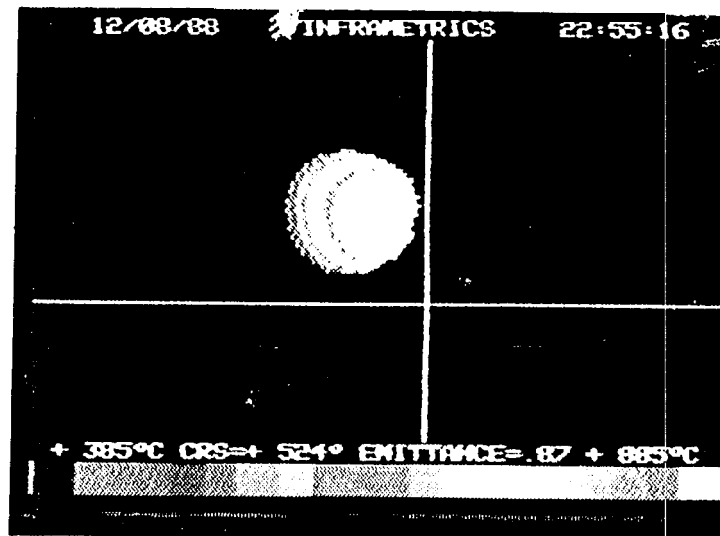
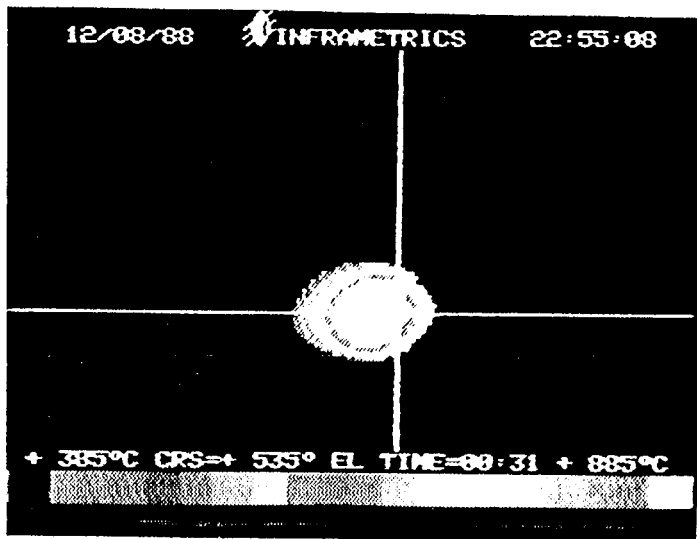
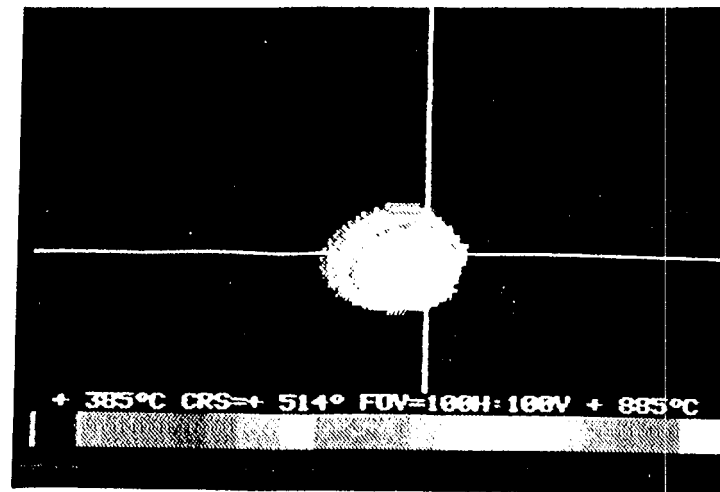
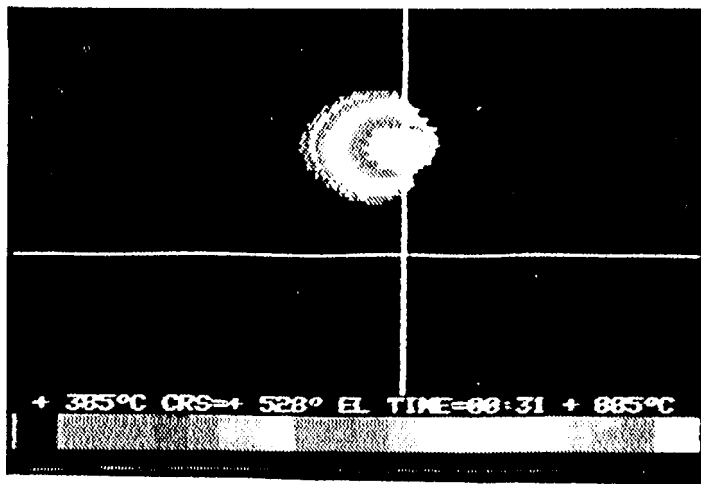


FIGURE 8

IRIMAGER OUTPUT DURING THE SPOT HEATING OF A LEVITATED SHUTTLE TILE SAMPLE IN 1 Go



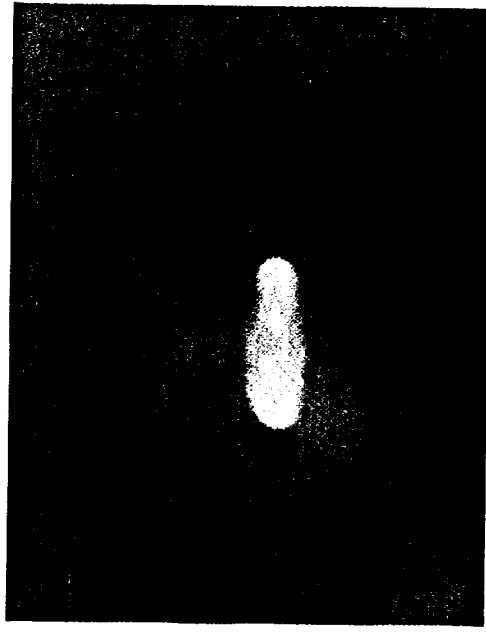
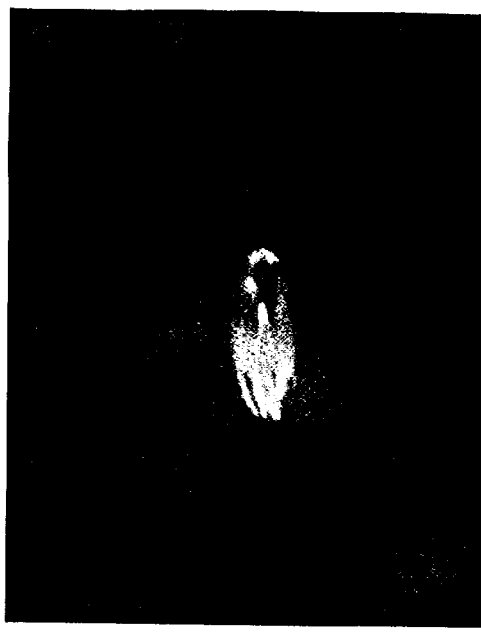
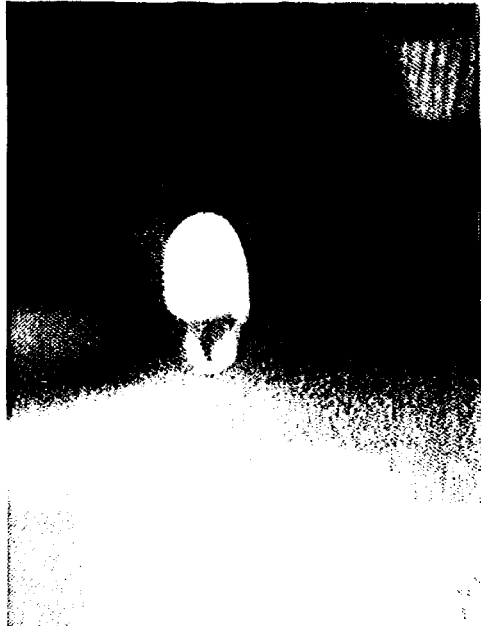
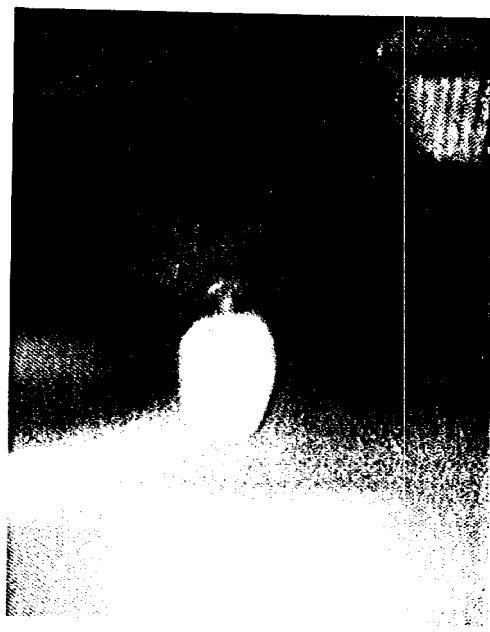
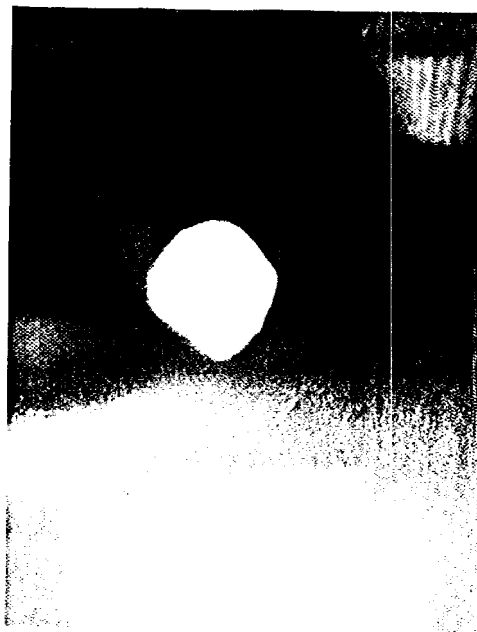


FIGURE 9

LOW GRAVITY MELTING AND SOLIDIFICATION OF O-TERPHENYL DURING PARABOLIC AIRPLANE FLIGHT

## ACKNOWLEDGMENT

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

## REFERENCES

1. Okress, E.C., Wroughton, D. M., Comenetz, G., Bruce, P. A., and Kelly, J.C.R. "Electromagnetic levitation of solid and molten materials", *J. Appl. Phys.* **23**,545-552 (1952)
2. Cummings, D.L., and Blackburn, D. A., "Oscillations of magnetically levitated aspherical droplets", *J. Fluid Mech.* 224, 395-416 (1991)
3. Rhim, W.K. , Chung, S.K., Man, K.F., Gutt, G., Rulison, A. and Spjut, R.E., "An electrostatic levitator for high temperature containerless materials processing in 1G", *Rev. Sci. Instrum.* 64,2961-2971 (1993)
4. Trinh, E.H. "Compact acoustic levitation device for studies in fluid dynamics and material science in the laboratory and microgravity", *Rev. Sci. Instrum.* 56, 2059-2065 (1985), and E.H. Trinh, J. Robcy, A. Arce, and M. Gaspar, "Experimental studies in fluid mechanics and materials science using acoustic levitation", *Mat. Res. Soc. Symp. Proc.* 87, 57-69 (1987)
5. Gopinath, A and Mills, A.F., "Convective heat transfer from a sphere due to acoustic streaming", *J. Heat Transfer*, 115,332-341 (1993)
6. Leung, E. W., Baroth, E., Chan, C. K., and Wang, T.G., "Thermal acoustical interaction and flow phenomenon", *AIP Conference Proceedings* 197,58-70, T.G. Wang Editor, New York, N.Y. (1989)
7. Fand, R.M. and Kaye, J., "The influence of sound on free convection from a horizontal cylinder", *J. of Heat Transfer* 83, 133-148 (1961)
8. Fand, R.M. "Mechanism of interaction between vibrations and heat transfer", *J. Acoust. Soc. Am.* 34, 1887-1894 (1962)
9. Trinh, E.H., "Levitation studies of the physical properties and nucleation of undercooled liquids", *Proc. VII European Symposium on Materials and Fluid Sciences in Microgravity*, ESA publication **SP-295**, 503-508 (1990)